USE OF ILLINOIS BY-PRODUCT RESIDUES FOR PAVING MATERIALS

N. Ghafoori[1], L. Wang[2], S. Kassel[3]
Department of Civil Engineering
Southern Illinois University at Carbondale
Carbondale, Illinois 62901

Keywords: coal, combustion residue, and roller compacted concrete

ABSTRACT
Tests were conducted in a field demonstration project to determine if by-products of fluidized bed and pulverized coal combustions (FBC and PCC) can be used in production of surface wearing course pavements for secondary/county roads. Various proportions of pre-hydrated FBC spent bed, as a fine aggregate; PCC fly ash, as a primary cementitious binder, with or without low dosage of portland cement; and crushed limestone coarse aggregate were blended at their optimum moisture content to produce zero-slump concrete mixtures. Pavement slabs of 6 ft by 12 ft were constructed by compacting 10 in. loose fresh matrix into 8 in. final thickness, in two lifts, using a self-propelled steel vibratory roller. No other surface finish treatments were used.

Information gathered in this paper makes the user of roller compacted concrete (RCC) containing FBC/PCC by-product residues aware of the fact that excellent engineering characteristics can be attained even when little or no portland cement is used. After 18 months from the date of initial casting, the pavement sections are crack-free and remain in excellent surface condition.

BACKGROUND
In the United States, nearly 80% of the coal produced is used for electric power generation and about 15% of this amount is recovered as coal combustion by-products[1]. Currently, 90 million short tons of ash is produced annually and the level of production is expected to reach 200 million short tons by the year 2000[2,3,4]. The high cost of waste disposal, scarcity of disposal sites, and serious environmental damages associated with the disposal of coal combustion residues have encouraged innovative utilization strategies. Undoubtedly, the construction industry, with its already depleted natural resources and ability to assimilate large volumes of materials, is in a unique position to provide safe and economical solutions of by-product utilization in a variety of construction-related applications.

While past laboratory investigation had provided valuable scientific data on the engineering properties of various FBC/PCC concrete mixtures and identified a number of potentially viable applications, field feasibility studies were needed to bring the laboratory investigation a step closer to reality[5,6]. The paper presented herein reports on a field demonstration project aimed at evaluating the constructability and engineering performance of the experimental slabs utilizing FBC spent bed and PCC fly ash. A nearly 300 ft road, comprising of 25 different slab sections, was constructed at a site located in Carterville, Illinois. Both conventional (vibratory) and roller compacted concrete placement techniques were utilized. Once the pavement sections were placed and finished, a coat of chemical sealant was spread on the slab surface to maintain sufficient moisture for the hydration of cementitious binders. The road was seal-cured for nearly two weeks before it was opened to traffic.

The findings of the surface course roller compacted slabs are presented and discussed in the paragraphs to follow.

MATERIALS AND METHODS
The FBC spent bed was obtained from a coal-fired circulating fluidized bed combustor at a co-generation plant burning high-sulfur Illinois coal. Its physico-chemical properties are shown in Tables 1 and 2. In order to eliminate the excess heat of hydration and subsequent expansive phases, the FBC residues were pre-hydrated prior to blending with other concrete constituents[7]. The fly ash selected for the study, a by-product of pulverized coal combustion process, complied with the requirements of ASTM C 618[8]. The chemical and physical characteristics associated with this fly ash are documented in Tables 1 and 3, respectively. A low dosage of Type V portland cement (5% by mass of total dry solids), as a complimentary cementitious binder, was used in some slab sections. The crushed limestone coarse aggregate was obtained from a quarry in southern Illinois.

---

[1]Associate Professor, [2]Research Graduate Assistant, and [3]Research Undergraduate Assistant

The physical properties are shown in Table 4. The mixture designation, solid constituents and proportions, nominal moisture content, and air-dry density are listed in Table 5.
Cylindrical (4" x 8") and beam-shaped (4" x 4" x 14") specimens were cored at different ages. They were tested for strength (ASTM C 39, ASTM C 496, and ASTM C 78)[9], elasticity (ASTM C 469)[9], length change (ASTM C 157)[9], resistance to wear (ASTM C 779, Procedure C)[9] and freezing and thawing (ASTM C 666, Procedure A)[9].

DISCUSSION OF RESULTS

The influence of mixture proportion, curing age, and testing condition on compression behavior of roller compacted FBC/PCC surface course slabs were investigated; and the results are presented in Figures 1 and 2. Similar to conventional concrete, the FBC/PCC mixes continued to gain strength with age. An average increase of 23% and 35% in compressive strength was attained when concrete age was extended from 60 to 90 and from 90 to 180 days, respectively, under dry conditions. When tested under wet conditions, the improvement in strength was 36 and 49% for the aforementioned periods. The compression properties also improved as the FBC spent bed to PCC fly ash ratio decreased. The increase in strength was higher under wet conditions (an average of 33%) than that obtained under dry conditions (a mean value of 18%). However, the influence of moisture (wet or dry) on compressive strength reduced as concrete age increased. Slabs without portland cement displayed compressive strengths superior to those obtained for pavement sections containing cement (21% and 10% for dry and wet compressive strength, respectively).

Table 5 demonstrates the variation of splitting-tensile strength with respect to time for the FBC/PCC core specimens. Similar to the compressive strength, the splitting-tensile resistance is a function of mixture proportion and fly ash content of the matrix. Insofar as strength development is concerned, roughly 83% of 90-day strength was achieved after 60 days from the date of initial casting. An average increase in splitting tensile strength of 15% was observed as concrete age was extended from 90 to 180 days. While the addition of portland cement did not improve the compressive strength, it enhanced the tensile splitting of RCC slabs. The average ratios of splitting-tension to compression were typical of those expected for conventional concretes.

Young's modulus of elasticity for the RCC slabs was determined at various ages, and the results are shown in Table 6. Static modulus of elasticity varied from 2.51×10^6 to 4.17×10^6 psi. The FBC/PCC roller compacted concrete exhibited a lower elastic modulus than that of conventional concrete of the same strength level.

The progression of flexural strength with respect to cementitious content is illustrated in Table 7. Based on the results obtained, the flexural strength of all matrices displayed a similar trend to those of compressive and splitting-tensile strengths; the flexural capacity steadily improved as the fly ash content of the matrix increased. When a low dosage of portland cement was incorporated into FBC/PCC mixtures, a slight improvement in flexural strength was observed (an average value of 4.4%).

Figure 3 documents the linear expansion of the surface course FBC/PCC roller compacted concretes. The strain properties of the field slabs was stabilized after 2-4 weeks from the date of construction and, to date, remain insignificant. The addition of portland cement reduced, to some extent, the overall expansion strain of FBC/PCC slabs.

Figure 4 illustrates the abrasion resistance of roller compacted concrete mixes under wet surface conditions. In general, the depth of wear increased with abrasion time, and the rate of increase in expansion was fairly uniform as time of wear increased. A reduction in FBC spent bed to PCC fly ash ratio or addition of a low dosage portland cement enhanced abrasion resistance of RCC slabs (12.5% decrease in abrasion wear with addition of portland cement). This improvement is attributed to a stronger cementitious mortar of the concrete surface which displayed more resistance to wear.

Resistance to rapid freezing and thawing of the beam-shaped specimens cored from the non air-entrained experimental slabs is shown in Table 8. The addition of fly ash, and to a great extent portland cement, increased the resistance to freezing and thawing. After a year of exposure to the freezing and thawing cycles of the winter climate, no deterioration or surface scaling has been experienced by any of the FBC/PCC roller compacted concrete slabs.

CONCLUDING REMARKS

In general, test results for FBC/PCC roller compacted concrete slabs were extremely encouraging. Strength and elastic modulus followed the well-known patterns of conventional concrete, and improved as cementitious content of the matrix increased. Expansion strains, based on internal sulfate attack, were minimal and virtually nonexistent. The slabs containing a low dosage of portland cement exhibited an improved tensile strength, linear expansion, abrasion wear, and freezing and thawing properties. Bi-weekly inspections of the paved surfaces indicated that, after 18 months from the date of initial casting, the sections are crack-free and remain in excellent surface condition.

ACKNOWLEDGEMENTS
This research was funded, in part, by grants made possible by the Illinois department of Energy and Natural Resources through its Coal Development Board and Illinois Clean Coal Institute, and by the U. S. Department of Energy (Grant number DE-FC22-92PC92521). However, any opinions, findings, conclusions, or recommendations expressed herein are those of the authors and do not necessarily reflect the views of IDENR, ICCI and the DOE.

Thanks are extended to a number of manufacturers who contributed materials used in this field project.

REFERENCES
1. Energy Information Administration "Cost and Quality of Fuels for Electric Utility Plants 1991", Office of Coal, Nuclear, Electric and Alternate Fuels, U.S. Department of Energy, Washington, DC 20585, August, 1992, 58 pp.
2. EPA report to Congress, "Wastes from the Combustion of Coal by Electric Utility Power Plants", United States Environmental Protection Agency, February, 1988, 45 pp.
3. Tyson, S.S., "Guidance for Coal Ash Use: Codes and Standard Activities for High-Volume Applications", Proceedings of 9th Annual International Pittsburgh Coal Conference, Pittsburgh, PA, 1992, pp. 815-817.
4. Coal Combustion Byproduct (CCB), "Production and Use: 1966-1993", Report for Coal Burning Utilities in the United States, American Coal Ash Association, Alexandria, VA 1995, 68 pp.
5. Ghafoori, N., "Engineering Characteristics and Durability of Roller Compacted Non-Cement FBC Mixes for Secondary Roads", Annual Report, Illinois Clean Coal Institute and Illinois Department of Natural Resources, September, 1994, 31 pp.
6. Ghafoori, N., "A Field Demonstration Project Utilizing FBC/PCC Residues for Paving Materials", Annual Report, Illinois Clean Coal Institute, September, 1995, 22 pp.
7. Ghafoori, N., and Sami, S., "A Simplified and Practical Approach for Effective Prehydration of Fluidized Bed Combustion Residues", Proceedings of the Coal, Energy and Environmental Conference, October 12-16, 1992, Ostrava, Czechoslovakia, Section IV, pp. 1-9.
8. Standard Specification for Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete, ASTM C 618, American Society for Testing and Materials, Philadelphia, PA, 1987, 3 pp.
9. American Society for Testing and Materials, Annual Book of ASTM Standard, Part 14 and 19, Philadelphia, PA, 1989.
10. American Concrete Institute (ACI) Committee 226, "Fly Ash in Concrete", ACI Materials Journal, 1987, pp. 381-410.
11. Ghafoori, N., and Chang, W.F., "Roller Compacted Concrete Utilizing Dihydrate Phosphogypsum, Journal of Transportation Research Record, September, 1990, Vol. 1, No. 1301, pp. 139-148.
12. Helmuth, R., "Fly Ash in Cement and Concrete", Portland Cement Association, SP040-OIT, 1987, 203 pp.
13. Mindess, S., and Young, Y.F., "Concrete", Prentice-Hall Inc., Englewood Cliffs, NJ, 1981, 671 pp.
14. Neville, A.M., "Properties of Concrete", John Wiley and sons, New York, NY, 1981, 779 pp.
15. Sukandar, B.M., "Abrasion of Concrete Block Pavers", Master Thesis, Department of Civil Engineering and Mechanics, Southern Illinois University, Carbondale, IL, January, 1993, 165 pp.
16. Yoder, E.J., and Witczak, A., "Principles of Pavement Design, 2nd Edition, John Wiley and Sons, 1975, 711 pp.

Table 1: Chemical Test Data of FBC Spent Bed and PCC Fly Ash

Chemical Composition	"FBC" Spent Bed	"PCC" Fly Ash	Fly Ash Specifications (ASTM C 618)
Silicon Oxide (SiO_2)	9.70	49.10	----
Aluminum Oxide (Al_2O_3)	3.69	25.50	----
Iron Oxide (Fe_2O_3)	2.16	16.60	----
Total ($SiO_2+Al_2O_3+Fe_2O_3$)	15.55	91.20	50.0 Minimum, Class C 70.0 Minimum, Class F
Sulfur Trioxide (SO_3)	24.42	0.50	50.0 Maximum
Calcium Oxide (CaO)	53.10	1.56	Less than 10%, Class F More than 10%, Class C
Magnesium Oxide (MgO)	0.88	0.89	----
Loss on Ignition	0.80	0.38	6.0 Maximum
Free Moisture	0.0	0.16	3.0 Maximum
Water of Hydration	2.65	0.0	----
Total Na_2O	0.16	0.37	----
Available Alkalies as Na_2O	N/A	0.08	1.5 Maximum
Total K_2O	0.39	2.26	----
Others ($TiO_2+P_2O_5+BaO$)	2.04	2.60	----

Table 2: Physical Properties of FBC Spent Bed

Fineness Modulus	Specific Gravity (OD)	Specific Gravity (SSD)	Absorption (%)	Organic Impurities
1.80	1.92	2.19	14.60	None

Table 3: Physical Properties of PCC Fly Ash

#325 Sieve Fineness		Specific Gravity	Autoclaved Expansion		Water Requirement		7-Day Compressive Strength		
Actual	Limit		Actual	Limit			Actual	ASTM	AASHTO
22.60	Max. 34%	2.39	0.03	0.80%	93.30	Max. 105	85.40	Min. 75%	Min. 60%

Table 4: Physical Properties of Crushed Limestone Coarse Aggregate

Maximum Size (Max. Normal Size)	Specific Gravity (OD)	Specific Gravity (SSD)	Absorption (%)	Rodded Unit Weight (OD) (lb/ft^3)	Rodded Unit Weight (SSD) (lb/ft^3)	Void Ratio
1 (3/4)	2.64	2.67	0.75	93.50	94.20	43.75

Table 5: Mixture Proportion Details for FBC/PCC Roller Compacted Concrete Mixtures

Mix No.	FBC Spent Bed (%) *	Silicious Fine Aggregate (%)	PCC Fly Ash (%)	Portlaud Cement (%)	Limestone Coarse Aggregate (%)	Nominal Moisture Content (%)	Air-Dry Density (lb/ft^3)
C3	26.67	----	13.33	----	60.0	7.67	144.47
C5	20.0	----	20.0	----	60.0	7.74	145.12
C1P	29.5	----	5.5	5.0	60.0	8.27	140.66
C3P	24.17	----	10.83	5.0	60.0	7.95	144.43
C5P	17.5	----	17.5	5.0	60.0	7.62	142.43

* Note: All percentages are by mass of total dry solids

Table 6: Splitting-Tensile Strength and Static Modulus of Elasticity of FBC/PCC Roller Compacted Concrete Mixtures

Mix No.	Splitting-Tensile Strength (psi)			Splitting-Tension to Compression Ratio			Modulus of Elasticity (10^6 psi)		
	Curing Age (Days)			Curing Age (Days)			Curing Age (Days)		
	60	90	180	60	90	180	60	90	180
C3	323	406	476	0.078	0.098	0.087	3.54	3.80	4.06
C5	442	500	549	0.103	0.092	0.096	3.70	3.94	4.17
C1P	236	300	362	0.111	0.110	0.108	2.51	2.78	3.09
C3P	352	438	530	0.106	0.109	0.120	3.30	3.48	3.66
C5P	467	536	571	0.120	0.119	0.121	3.41	3.60	3.79

Table 7: 90-Day Flexural Strength of FBC/PCC Roller Compacted Concrete Mixtures

Mix. No.	Flexural Strength (psi)	Strength Ratio	
		Flex./Comp.	Flex./Split
C3	646.88	0.127	1.60
C5	701.25	0.128	1.40
C1P	486.3	0.189	1.62
C3P	665.35	0.165	1.52
C5P	743	0.165	1.39

Table 8: Freezing and Thawing of FBC/PCC Roller Compacted Concrete Mixtures (Mass Loss %)

Mix No.	Number of Freezing and Thawing Cycles								
	5	10	15	20	25	30	35	40	45
C3	0.43+	7.42#	17.1#	30.5#					
C5	0	0.41+	0.41+	1.03*	3.08#	44.8#			
C1P	0.44-	2.44+	22.6#	41.2#					
C3P	0.21-	0.42-	5*	15.2#	55.7#				
C5P	0	0	0.22-	0.43-	1.3+	4.11+	10.6#	29.2#	

- slight flaking; + slight chipping; * noticeable cracking in specimen; # severe flaking and chipping

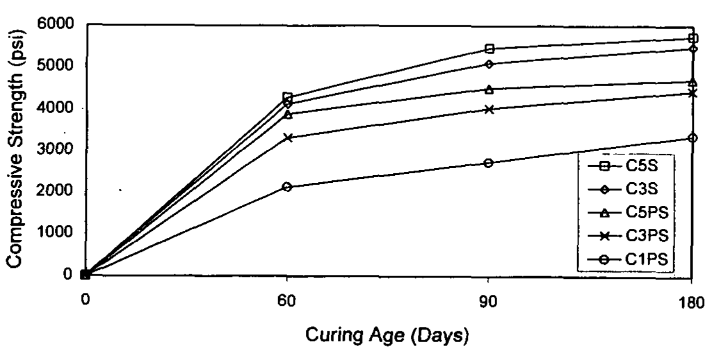

Figure 1: Field Air-Dry Compressive Strength of Surface Course FBC/PCC Roller Compacted Concrete Mixtures

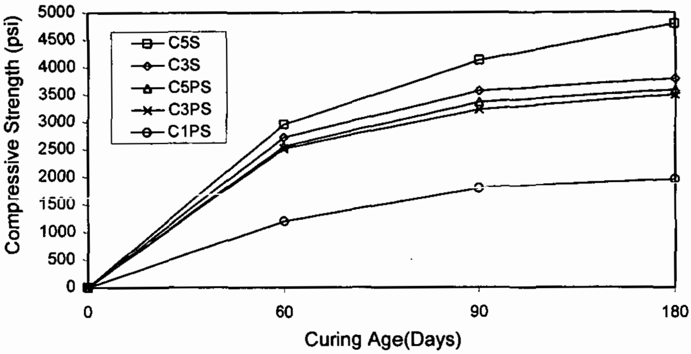

Figure 2: Field *Soaked* Compressive *Strength of Surface* Course FBC/PCC Roller Compacted Concrete Mixtures

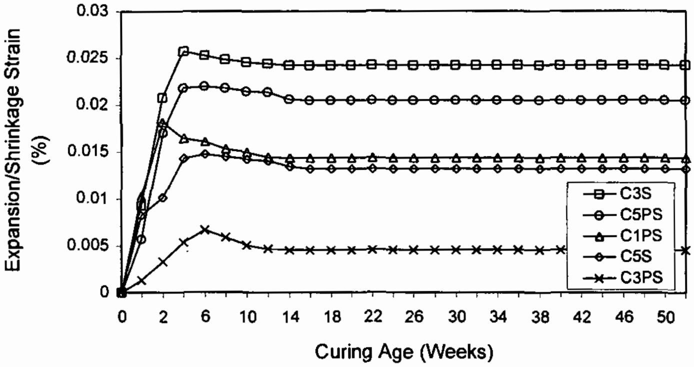

Figure 3: Field Expansion/Shrinkage of Surface Course FBC/PCC Roller Compacted Concrete Mixtures

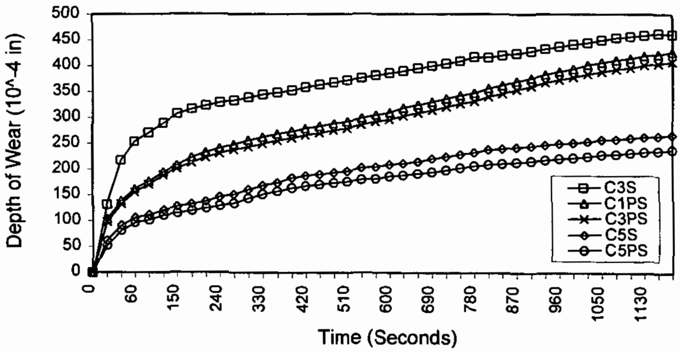

Figure 4: Field Abrasion Resistance of Surface Course FBC/PCC Roller Compacted Concrete Mixtures (Wet at Testing)